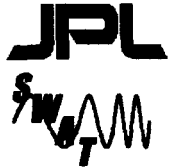




Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz



Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Speaker: Frank Maiwald

***Erich Schlecht
Goutam Chattopadhyay
Alain Maestrini
John Gill***

Imran Mehdi

Jet Propulsion Laboratory, Pasadena, CA 91109

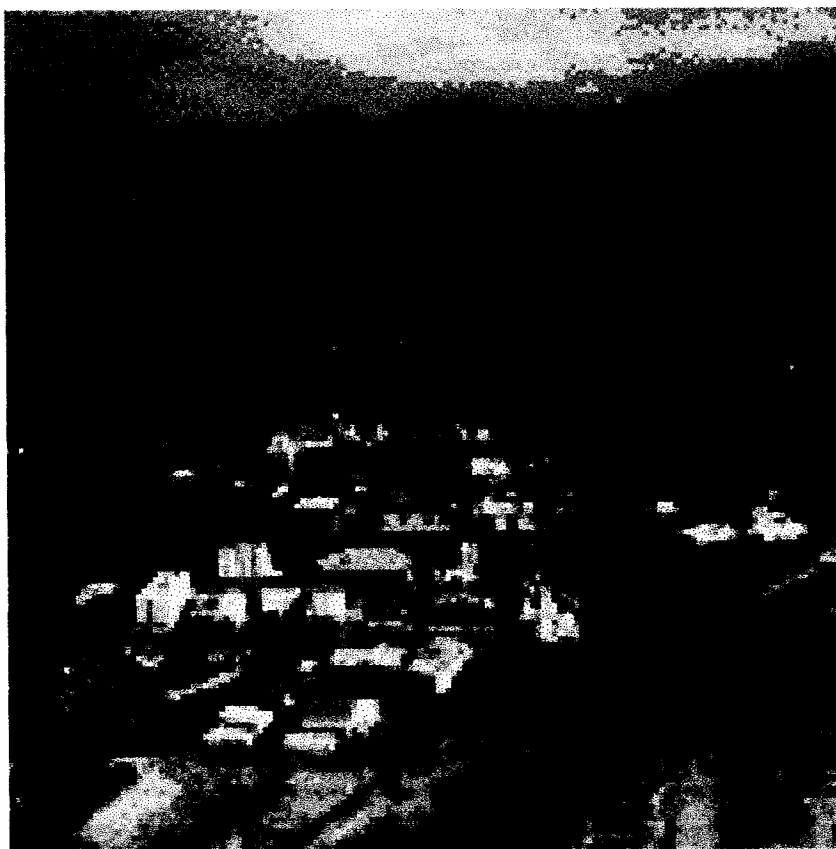
Presentation at the Universitaet zu Darmstadt, Germany

May 27-29, 2002



Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Jet Propulsion Laboratory, Pasadena California USA



<http://www.jpl.nasa.gov/index.html>

Jet Propulsion Laboratory
California Institute of Technology

JPL HOME

JPL's Aerogel Named World's Lightest Solid

A new version of aerogel, the particle-collecting substance on NASA's Stardust spacecraft, has been recognized by Guinness World Records as the solid with the lowest density.
[Stardust home page](#)

Global Surveyor Adds to Its Martian Photo Album

A view of the red planet almost completely enveloped in dust storms is one of 15,251 newly released images from NASA's Mars Global Surveyor.
[More Mars images](#)

Spotlight: Wiring Future Fashion Trend

Looking for the ultimate accessory? Someday, you might be able to wear your computer. JPL engineer Ann Devereaux is hard at work developing the Wearable Augmented Reality Prototype (Warp), a personal communication device.
[Browse Image](#)

Aqua carries atmosphere instrument into orbit

NASA's latest Earth observing satellite, Aqua, carrying the NASA Jet Propulsion Laboratory-managed Atmospheric Infrared Sounder instrument, successfully launched early Saturday, May 4. Aqua is dedicated to advancing our understanding of Earth's water cycle and our environment.

May 7, 2002

MISSION TO THE PLANETS

EARTH
MARS
JUPITER
SATURN

Upcoming Lecture:

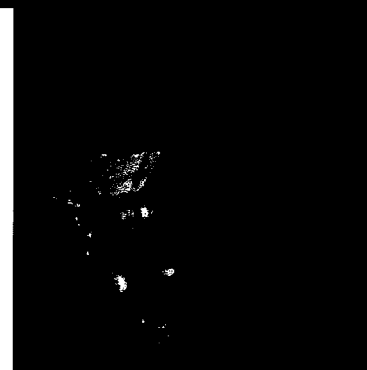
JPL will not be holding Open House in May

Favorite Images

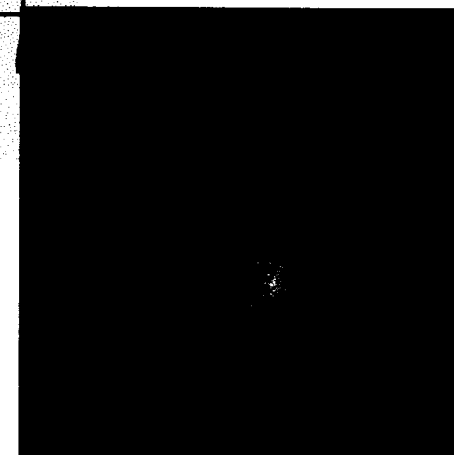
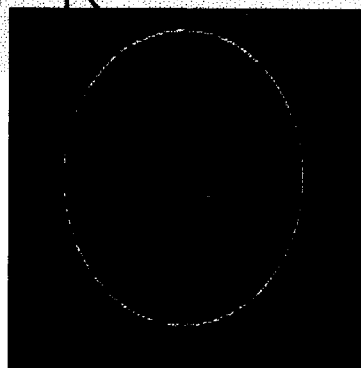
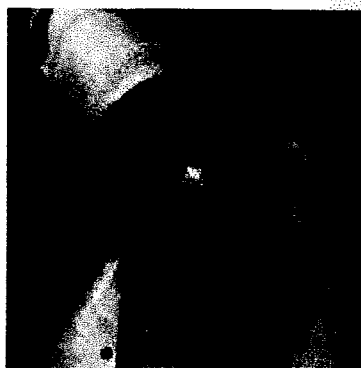
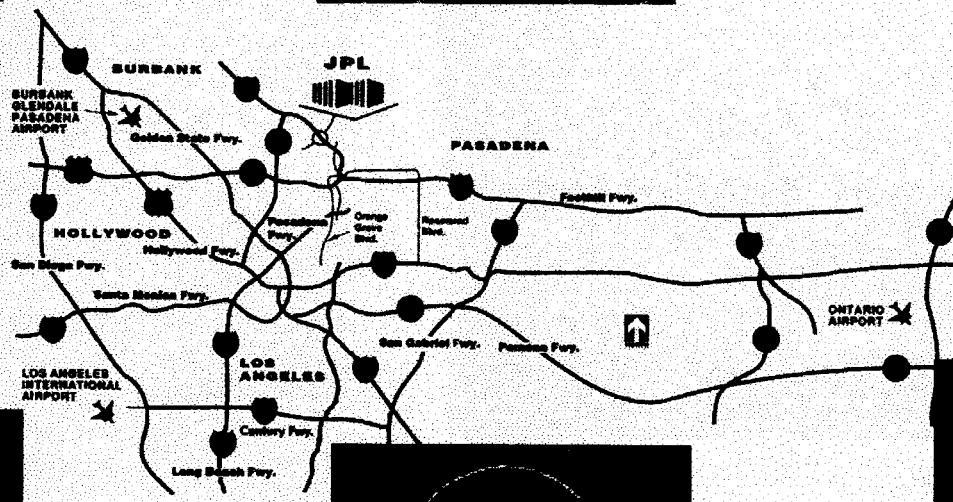
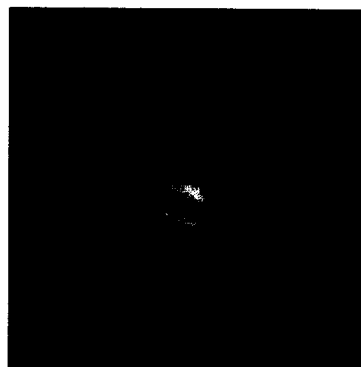
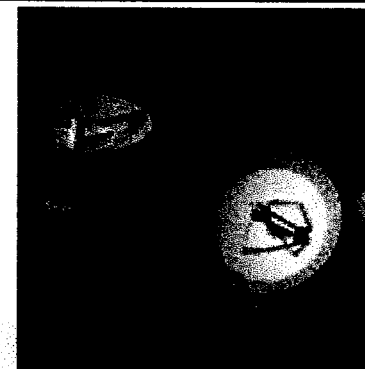
Sydney blanketed by smoke from fires
[More Images](#)



Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz



Greater Los Angeles Area





OUTLINE

- ◆ Motivation
- ◆ Frequency multiplier chains
- ◆ Devices used for the frequency multipliers
- ◆ Simulations and diode model
- ◆ Technology flowchart of GaAs Monolithic Membrane Diode (MoMeD) Circuits
- ◆ Low frequency designs
- ◆ High frequency designs
- ◆ Measurements on reliability
- ◆ Discussion



Motivation

Development of components for space-based heterodyne sensor technology at mm and submillimeter wavelengths

for

Astrophysics, Earth and Planetary Heterodyne Remote Sensing Instruments (Herschel Space Observatory, EOS-MLS, ROSETTA).

High-resolution spectroscopy of molecular species

HD (1-0) transition line at 112 μ m to determine H/D ratio

High resolution spectroscopy: CII and NII hyperfine structure chemistry in InterStellar Medium (ISM)

Specific Technology Goal

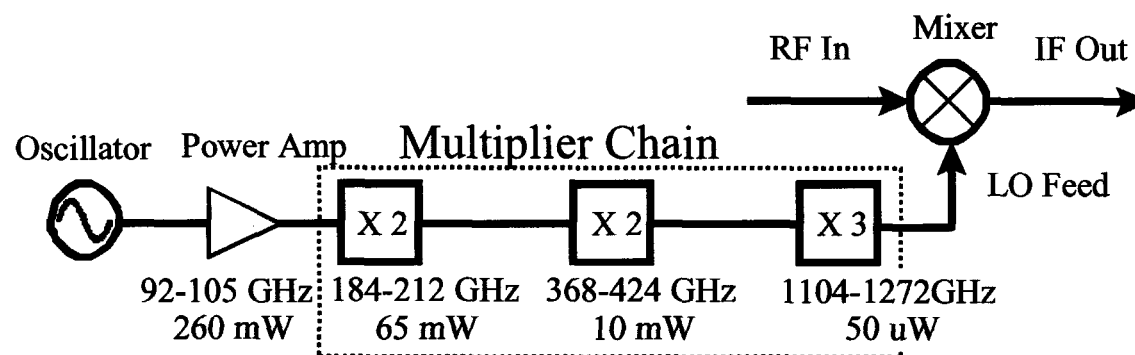
Fabrication of GaAs based circuits at JPL

- Low frequency circuits (< 1THz) with reduced substrate**
- High frequency circuits (>1THz) with an monolithic membrane diode (MoMeD)**



Frequency multiplier chain up to 3THz

Example: Power amplifier module, 200GHz and 400GHz doubler, 1200GHz tripler



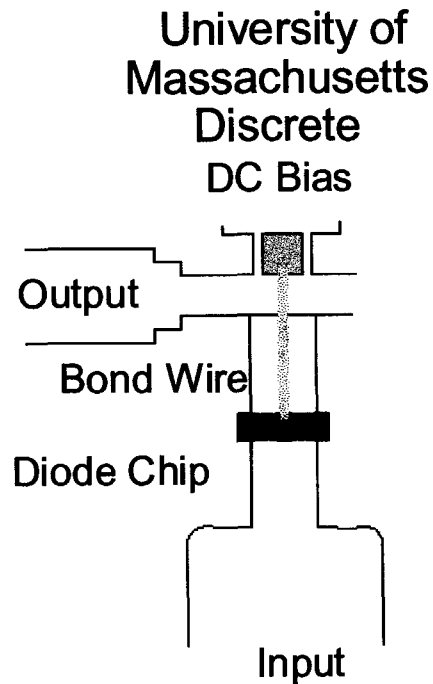


- ◆ Ruggedness, resistance to shock and vibration for space qualification.
- ◆ Wide bandwidth (10 to 14 %).
- ◆ High power capability (200 – 250 mW).
- ◆ High efficiency for multiple cascaded stages.
- ◆ Improved performance at low temperatures.

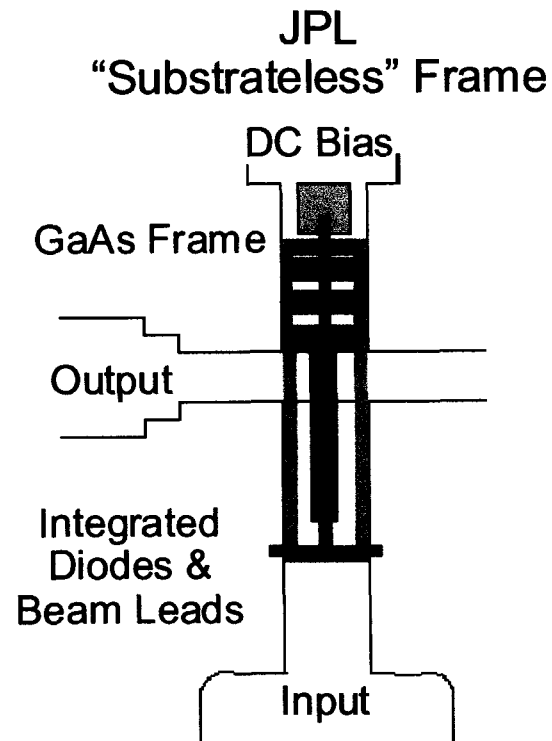


Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

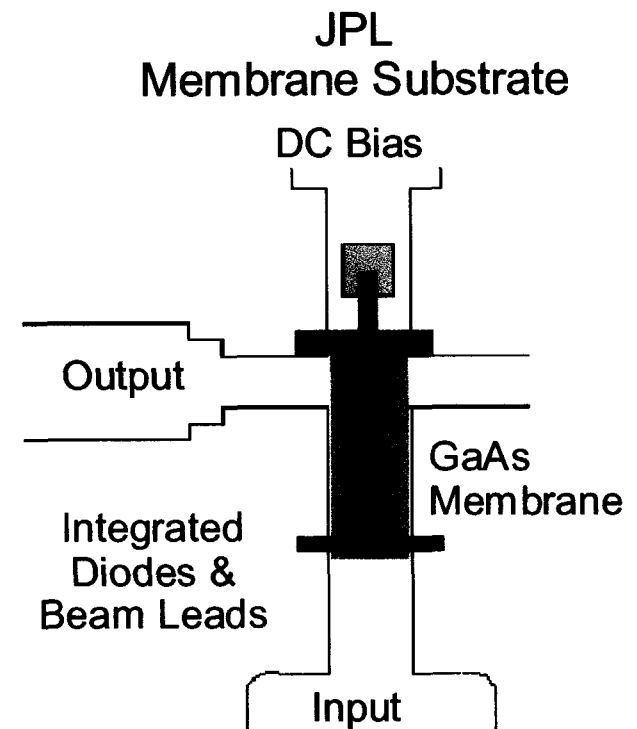
Planar Balanced Doubler Technologies Fabricated at JPL



- ! Chip soldered to block
- ! Bondwire connects chip to DC Bias Cap



- ! All chip connections to block made with beam leads
- ! Diodes integrated into circuit
- ! GaAs under metal removed for low loss

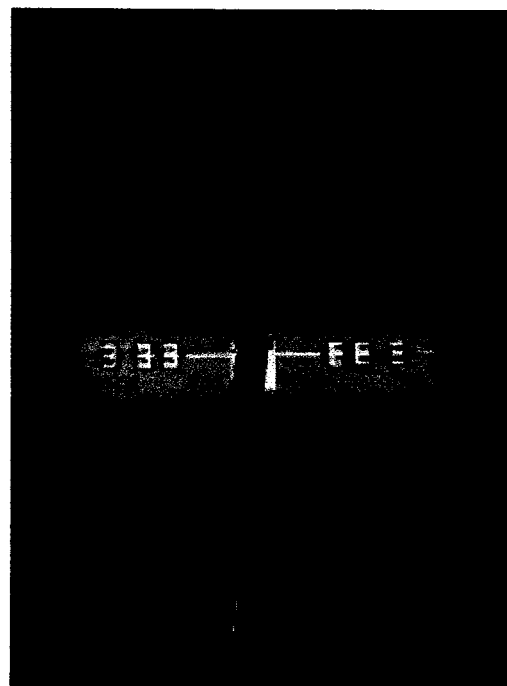


- ! Circuit fabricated on 3 mm GaAs membrane
- ! Block connections made with beam leads



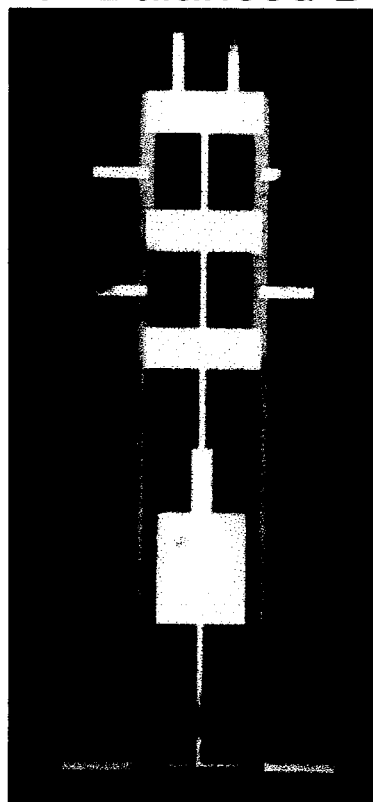
Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Photos of Planar Balanced Doubler Types



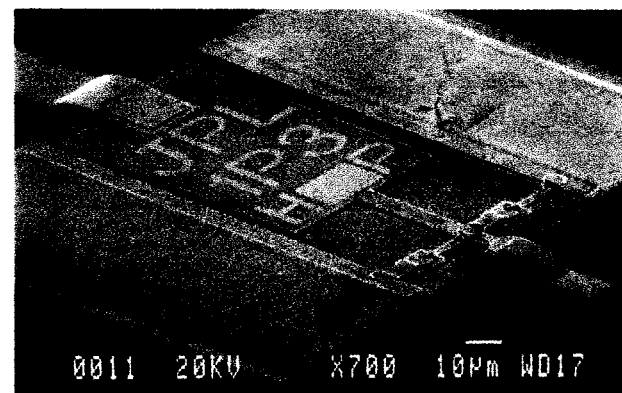
600 μm

Discrete



250 μm

Monolithic substrateless

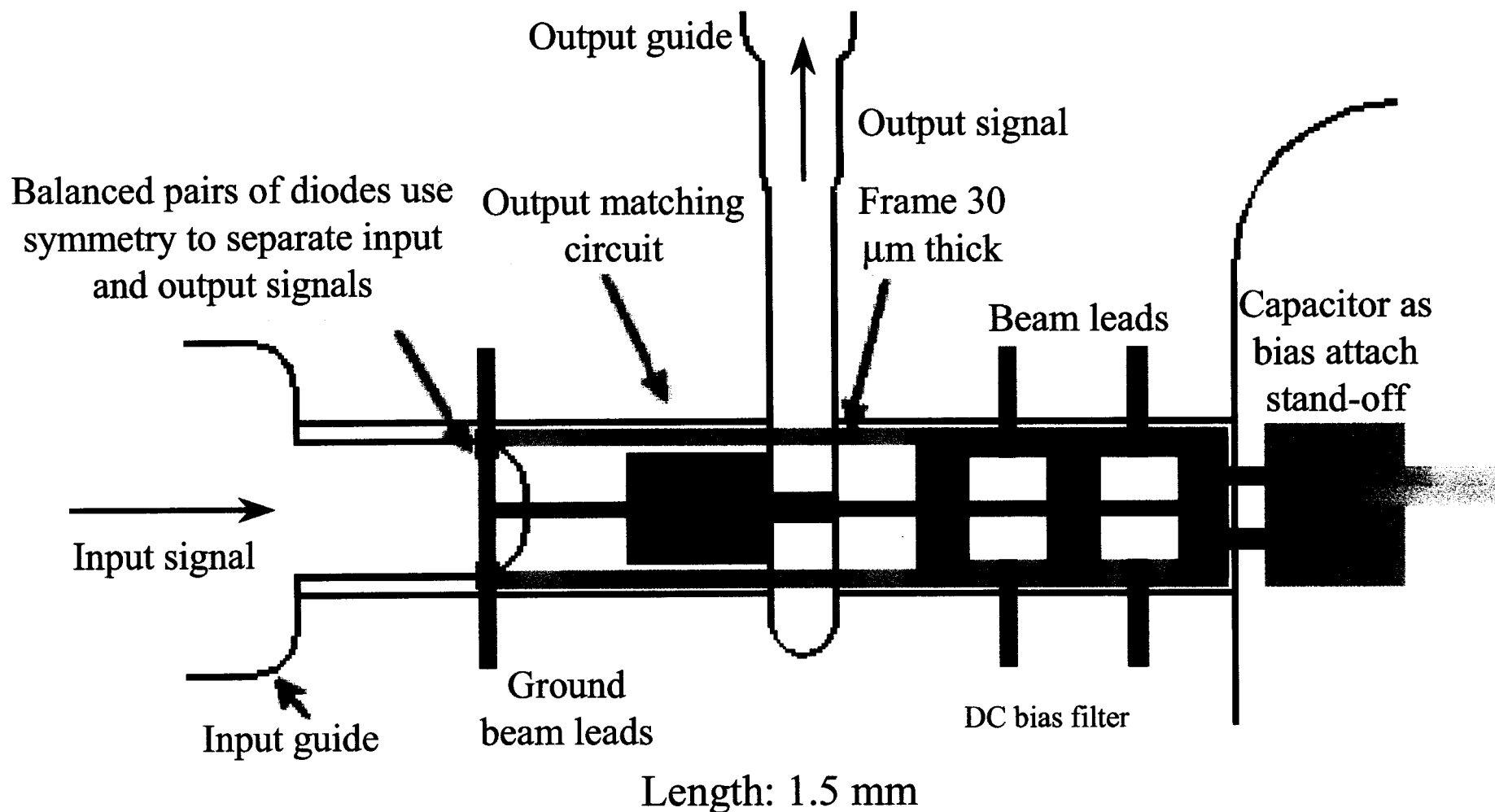


Monolithic membrane



Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

400 GHz Substrateless Circuit in Block

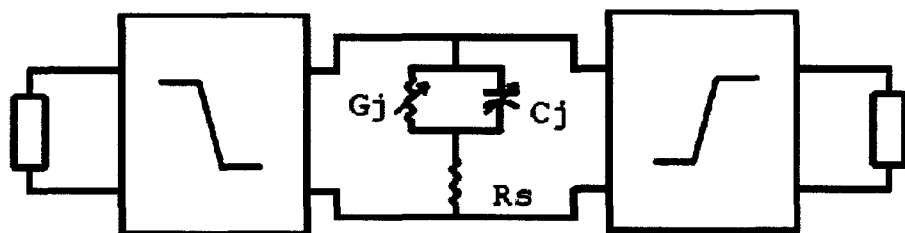




Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

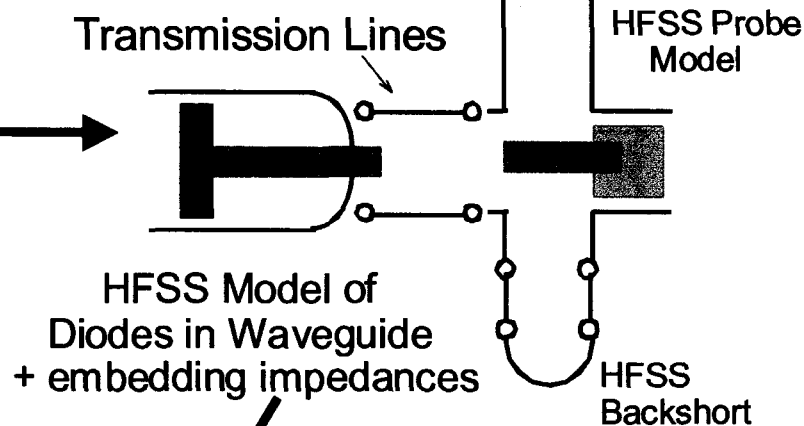
Three-Step Doubler Design Strategy

1st Step Optimize Diode

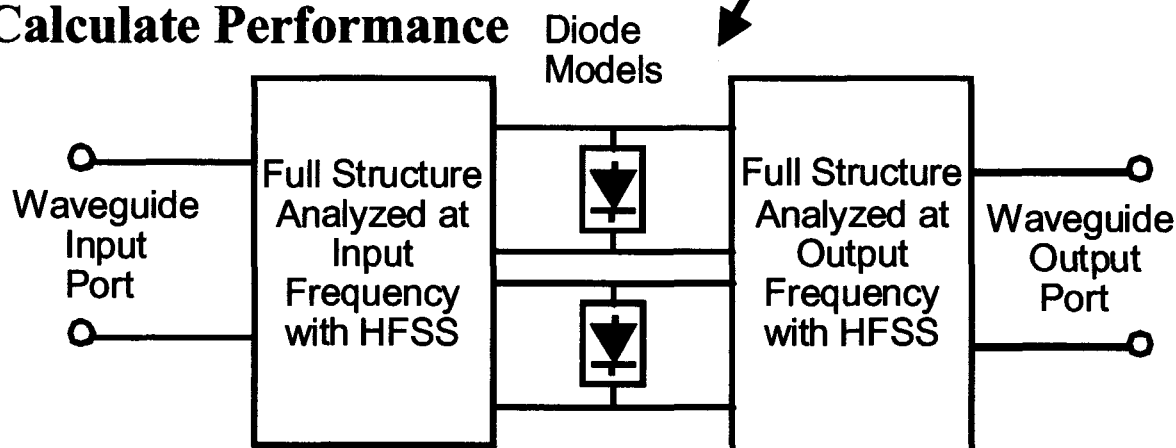


Optimize diode size and find embedding impedances using harmonic balance simulator and diode model.

2nd Step Design Linear Circuit



3rd Step Calculate Performance

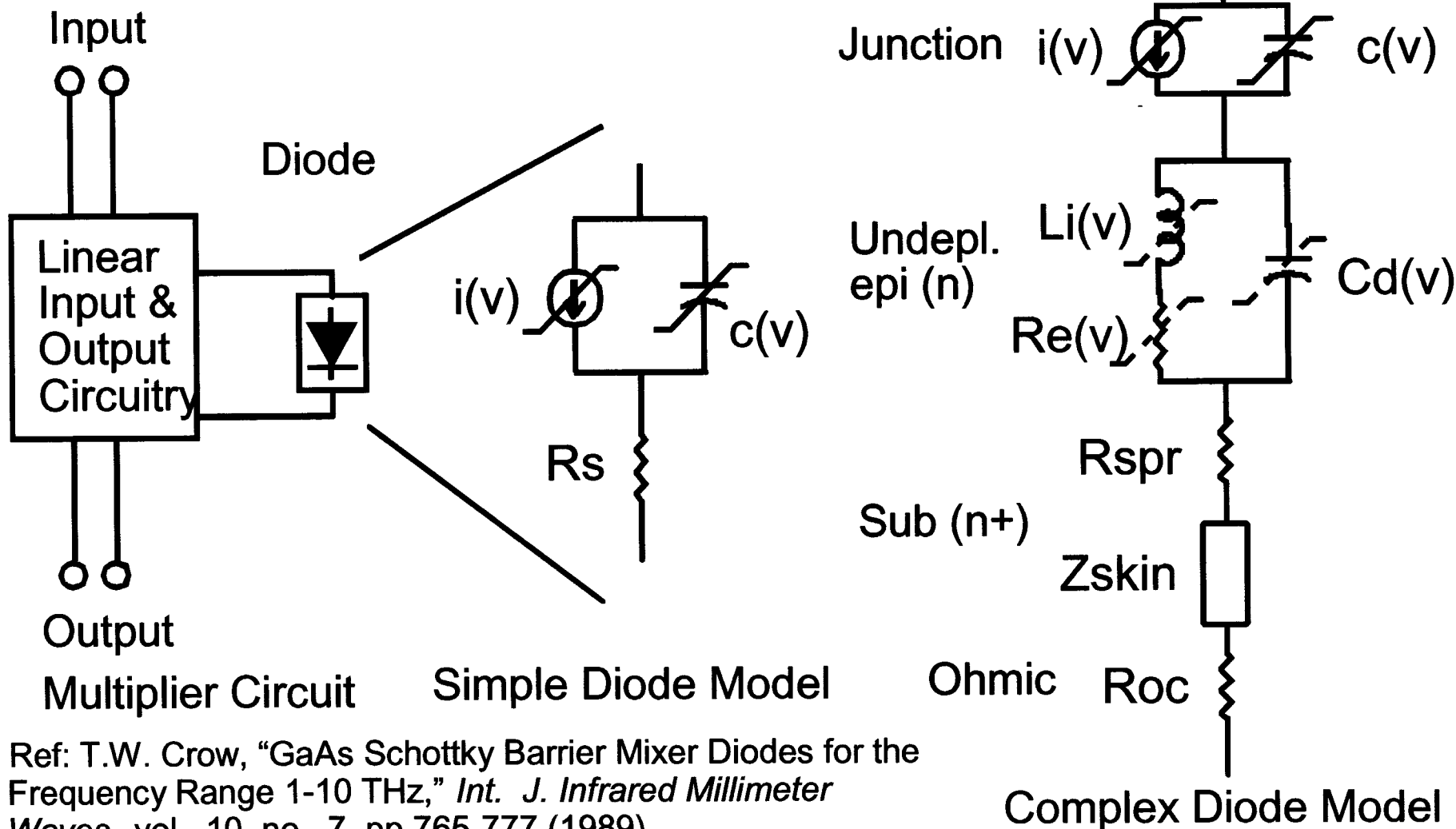


4th Step Iterative Full Circuit Optimization



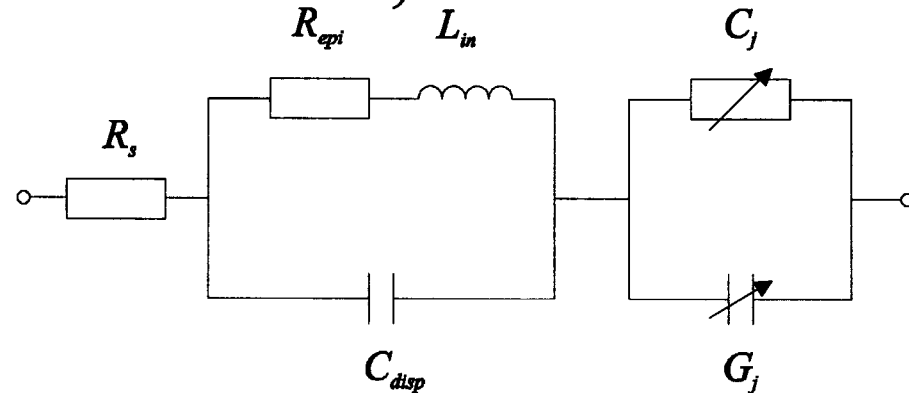
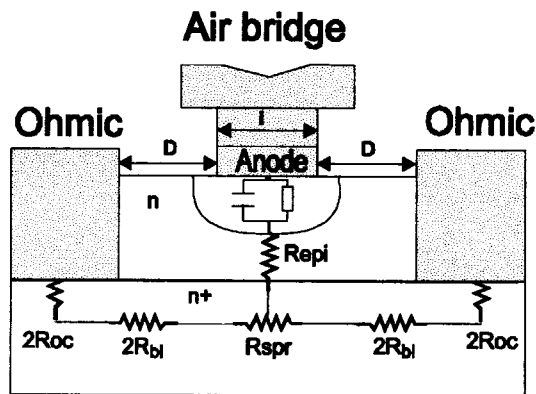
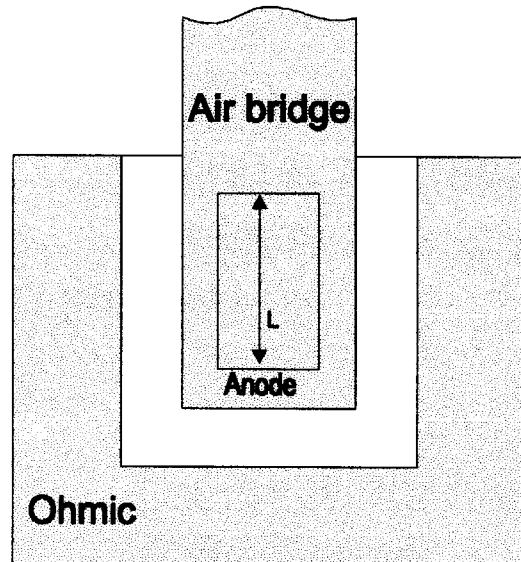
Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Diode Modeling



Ref: T.W. Crow, "GaAs Schottky Barrier Mixer Diodes for the Frequency Range 1-10 THz," *Int. J. Infrared Millimeter Waves*, vol. 10, no. 7, pp 765-777 (1989)

JPL Schottky diode model, cont'd



$$C_j = \frac{Ll \cdot \epsilon_s}{W} \left(1 + 4D_1 \frac{(L+l)W}{Ll} \right) = \frac{A\epsilon_s}{W} \gamma_c \quad I_m = AN_d q v_m \gamma_c$$

$$R_{spi} = \rho_{spi} \times \frac{t_{spi} - W}{l \times L} \times \gamma_r \quad R_{bl} = \rho_{bl} \times \frac{D}{(2 \times L + l) \times t_{bl}}$$

$$R_{spr} = \rho_{spr} \times \frac{l}{12 \times L} \quad R_{oc} = \frac{\sqrt{\rho_{oc} \times \rho_{bl}}}{2 \times L + l}$$



JPL Schottky diode model

Includes:

- Electron velocity saturation
- Breakdown
- Edge effects
- Temperature dependency of electron mobility
- Some frequency dependency of the R_s (skin effect in n^+)

As a function of:

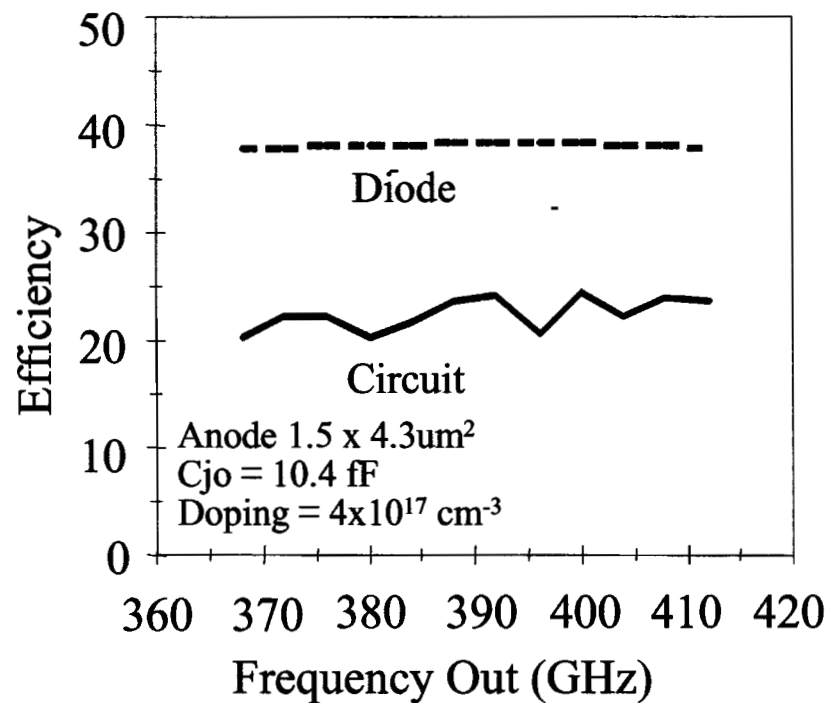
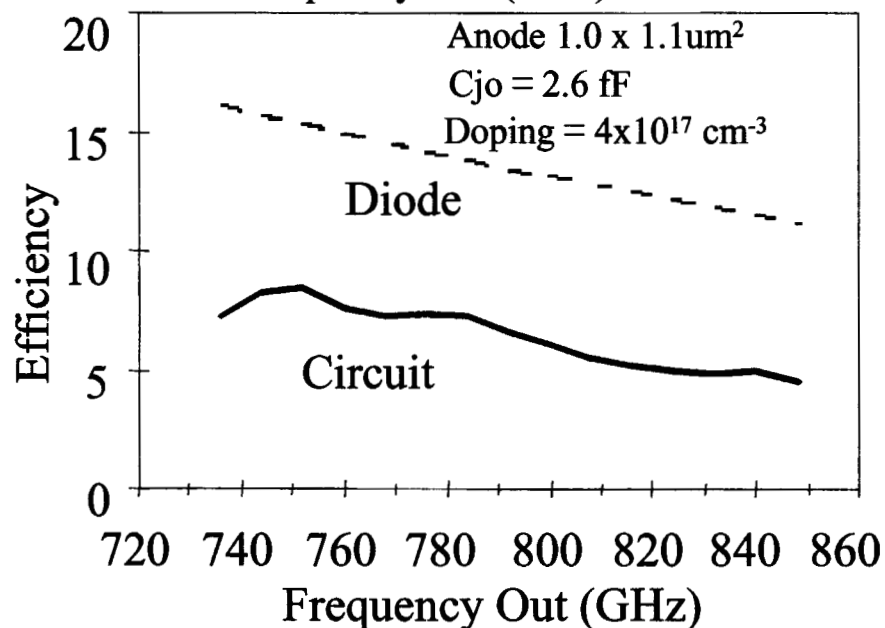
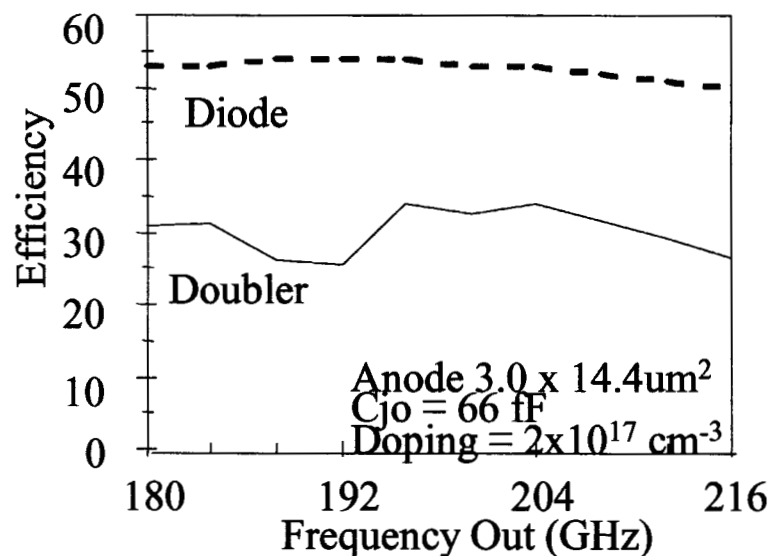
- Junction size (L, I)
- Epilayer thickness and doping (t_{epi}, N_d)
- Temperature (T)

Allows:

optimization of the diode parameters (L, I, N_d) for given frequency and power to maximize multiplier efficiency.



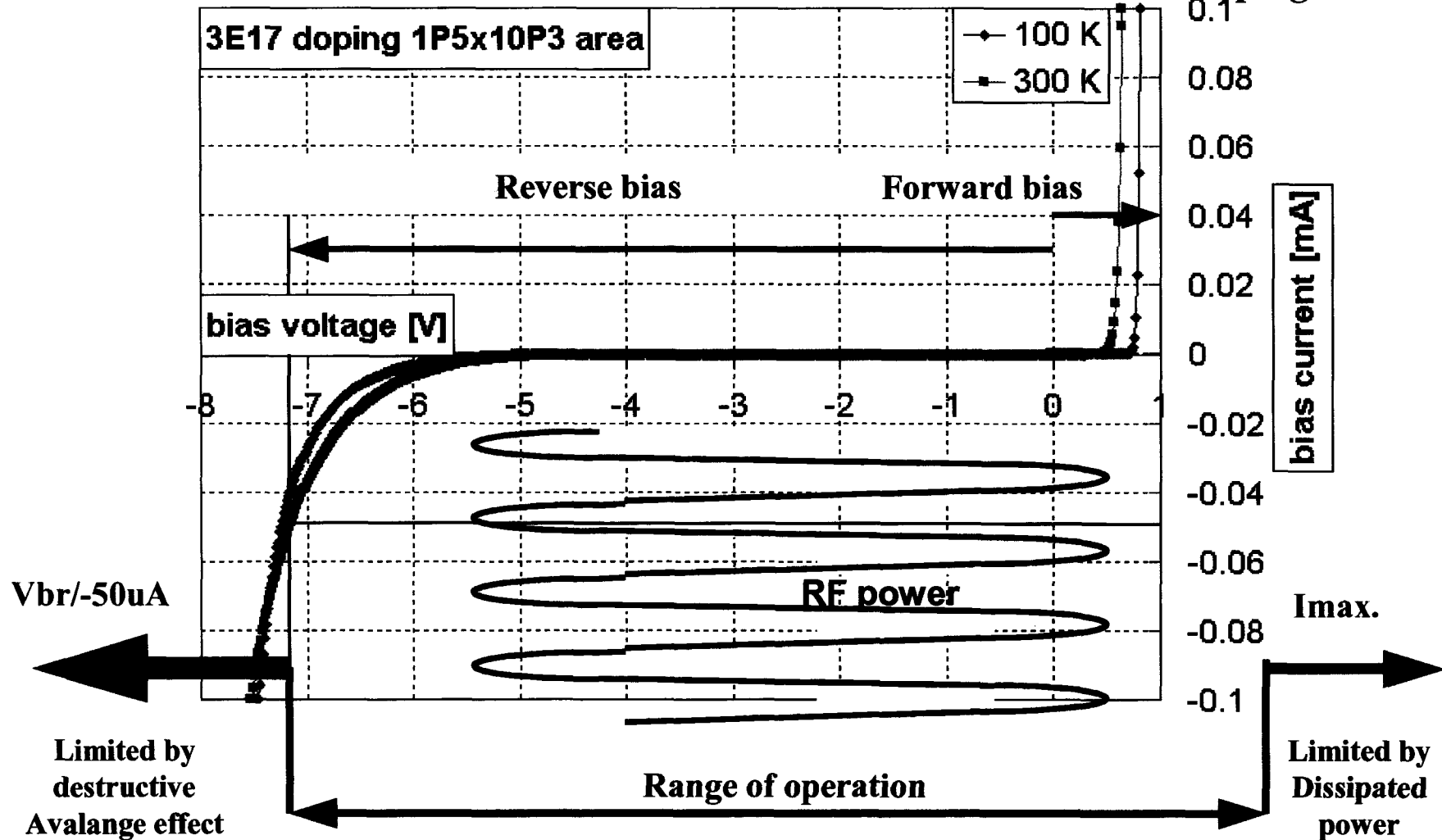
Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz





Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Measured I/V curve at 300K and 100K for one diode with $3E17$ doping

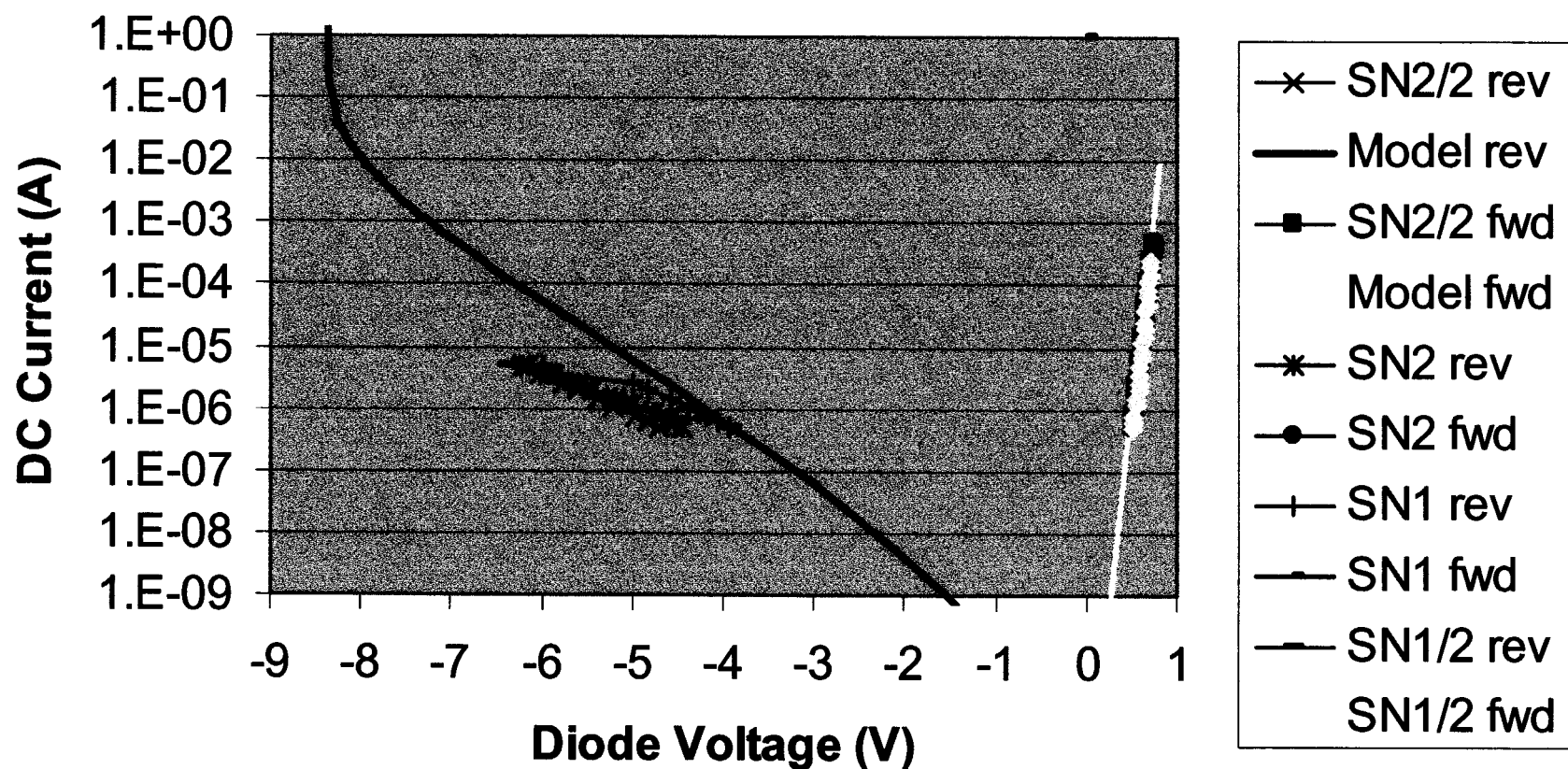




Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz



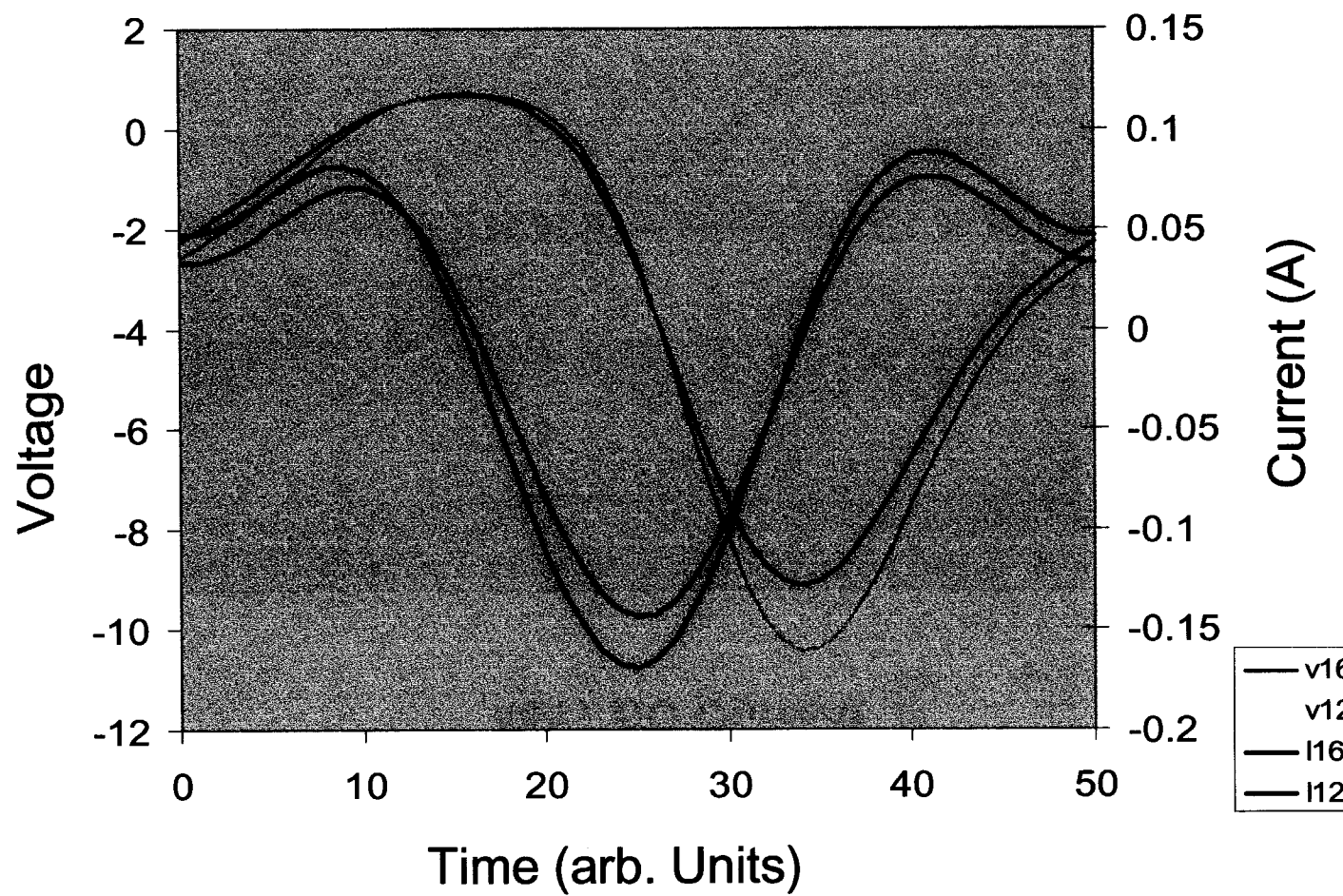
4e17 DC Current





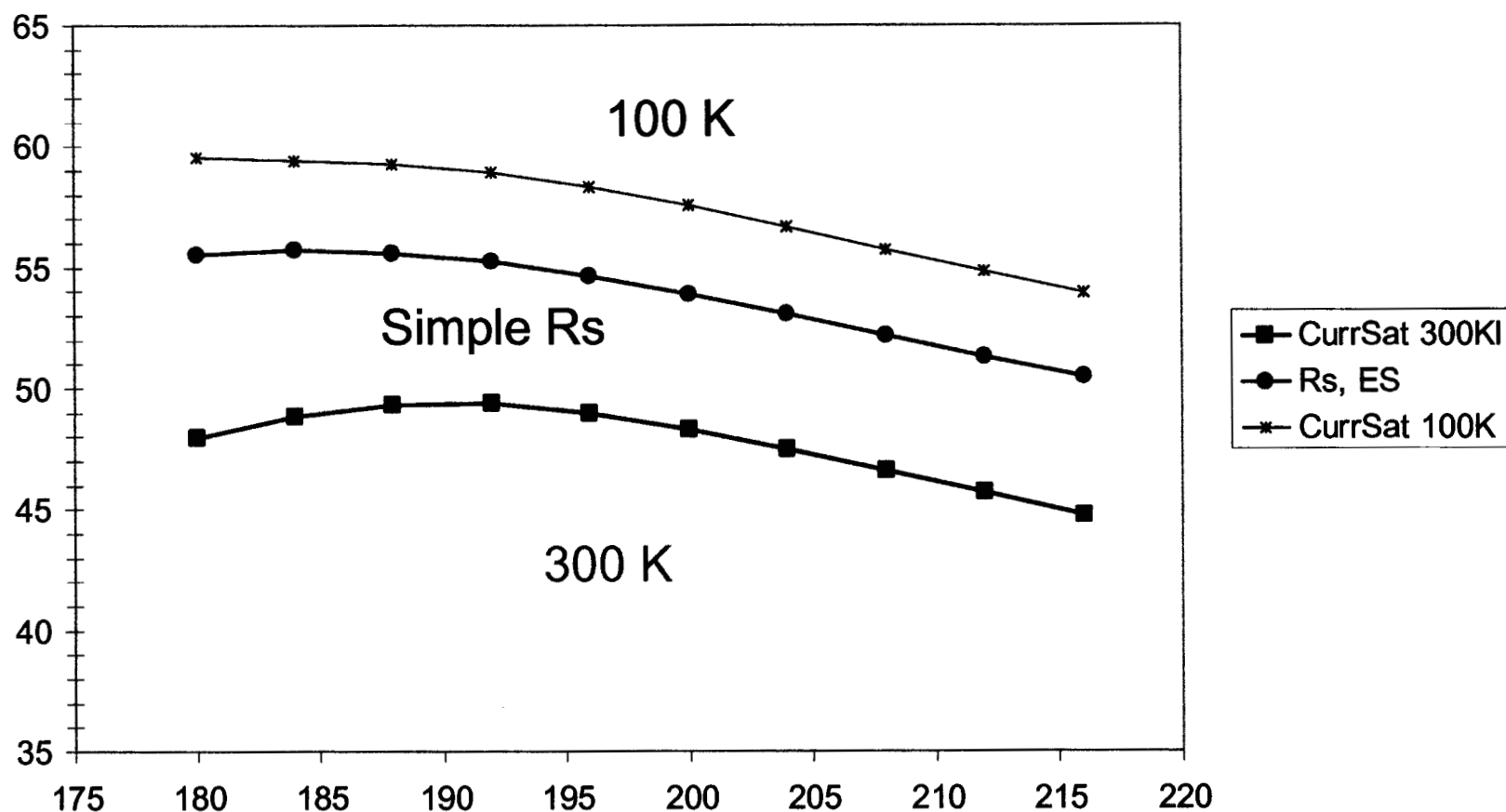
Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Typical Waveforms for Two Diode Sizes





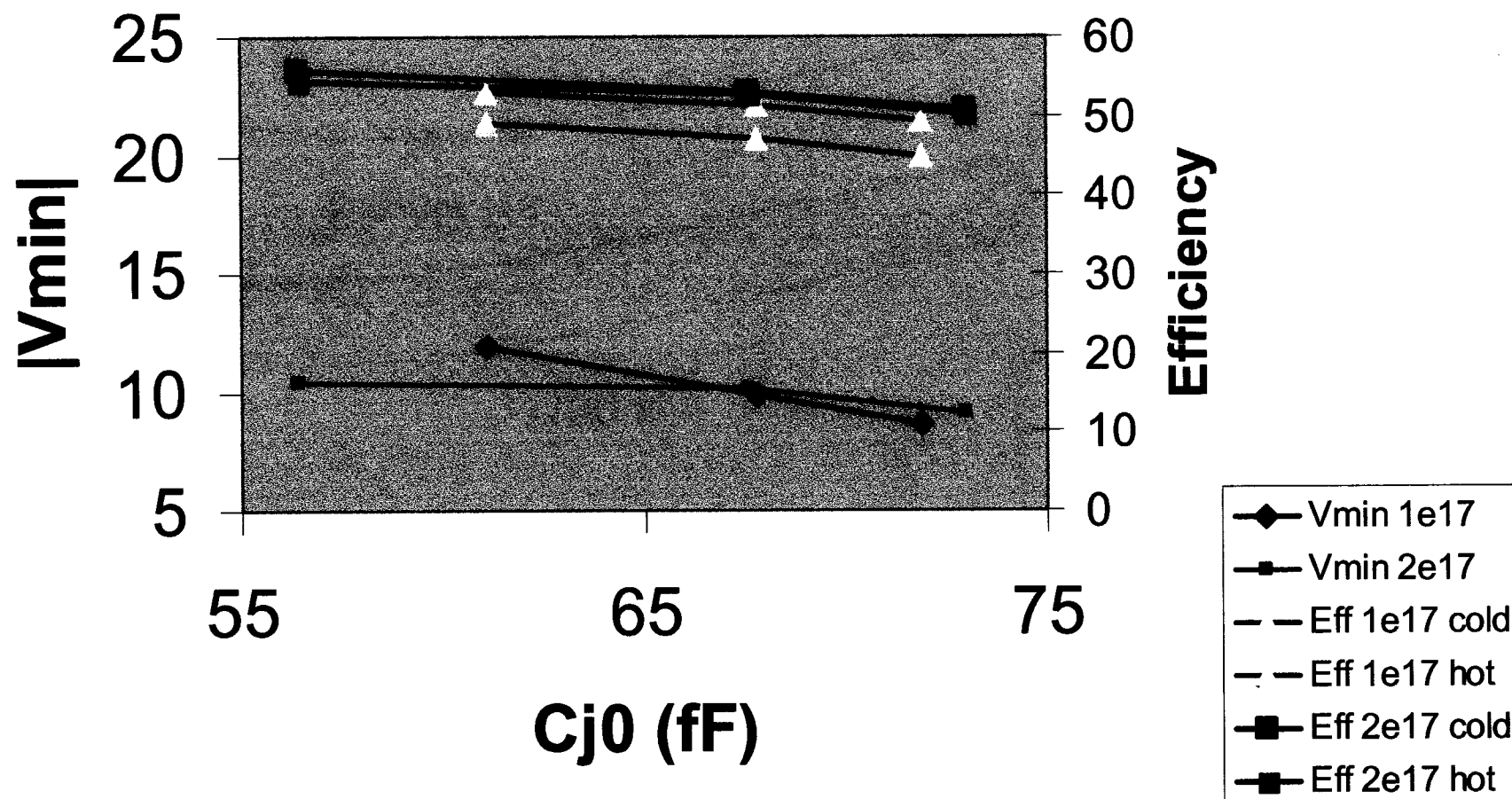
Low-Temperature, High Temperature and Simple Model Diode Efficiency Prediction for Same Circuit





Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

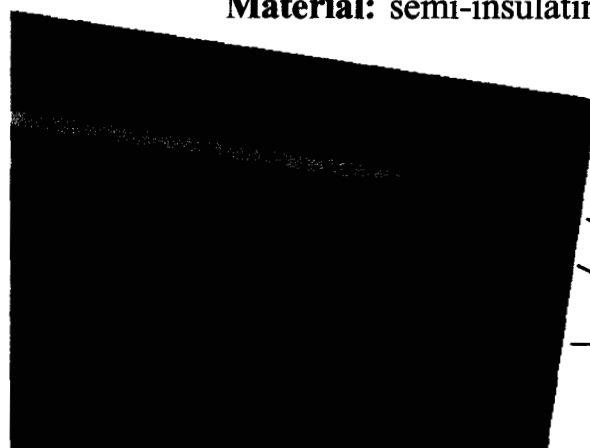
Effect of Temperature and Doping on Efficiency and Voltage Peaks



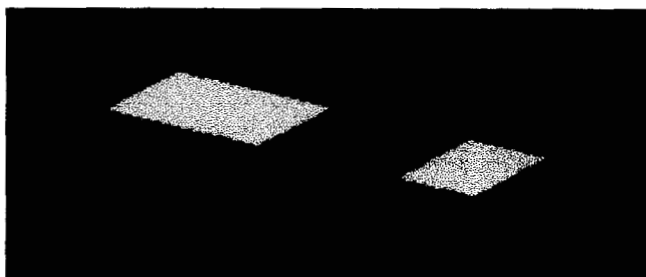


Technology flowchart of GaAs Monolithic Membrane Diode (MoMeD) Circuits,

Material: semi-insulating GaAs wafer with epitaxial layers grown by MBE or MOCVD



- n^- GaAs, $\sim 200\text{nm}$ thick doped $2-5 \times 10^{17} / \text{cm}^3$ (Schottky-layer)
- n^+ GaAs, ~ 1.5 micron thick heavily doped ($5 \times 10^{18} / \text{cm}^3$)
- $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$, $\sim 50\text{nm}$ etch-stop layer
- Intrinsic GaAs membrane layer, $3\mu\text{m}$ thick
- 400nm thick AlGaAs etch stop
- SI (substrate intrinsic) GaAs

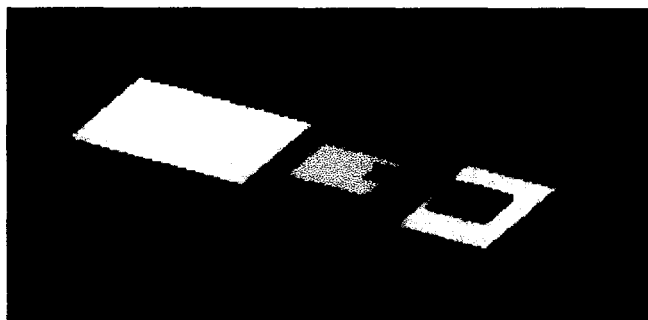


- recessed Ohmic contacts into the n^+ GaAs layer, alloyed Au/Ge/Ni/Ag/Au metalization
- Mesa definition by selective dry etch of BCl_3 , SF_6 , and Ar in an electron cyclotron resonance (ECR) reactive ion-etch system (RIE)
- Interconnect metal (gold)



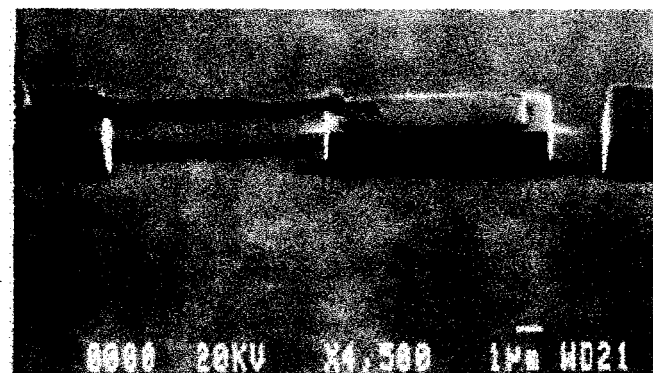
Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Technology flowchart of GaAs Monolithic Membrane Diode (MoMeD) Circuits



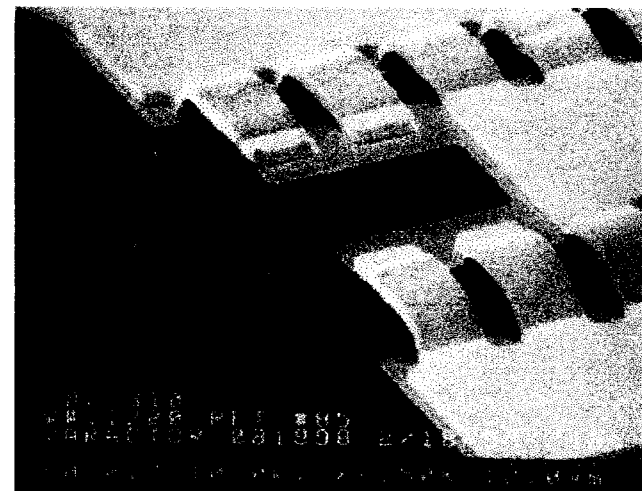
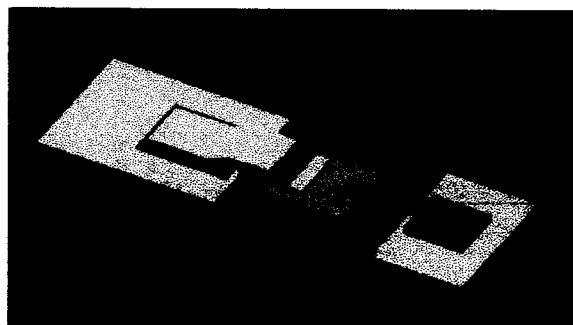
•E-beam anode

A second layer of patterned photoresist provides the stencil for the Ti/Pt/Au Schottky and interconnect metal.

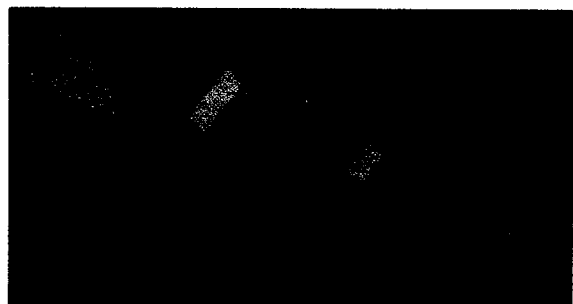




Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz



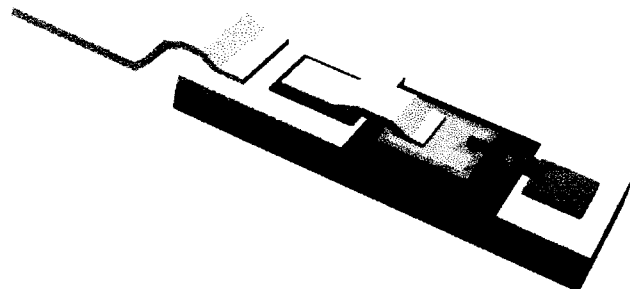
Rectangular Schottky diode



- SiN, silicon nitride is deposited using plasma enhanced chemical vapor deposition (PECVD), isolator for MIM capacitors

- Bridge/capacitor metal

- Membrane definition
- Bridge metal/RF probe/beam leads



- substrate removed, GaAs substrate is thinned to the desired thickness (12-50 mm) by lapping, polishing and wet etching
- circuits are separated and can be removed from the carrier wafer by dissolving the mounting wax and collecting the chips on filter paper

Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

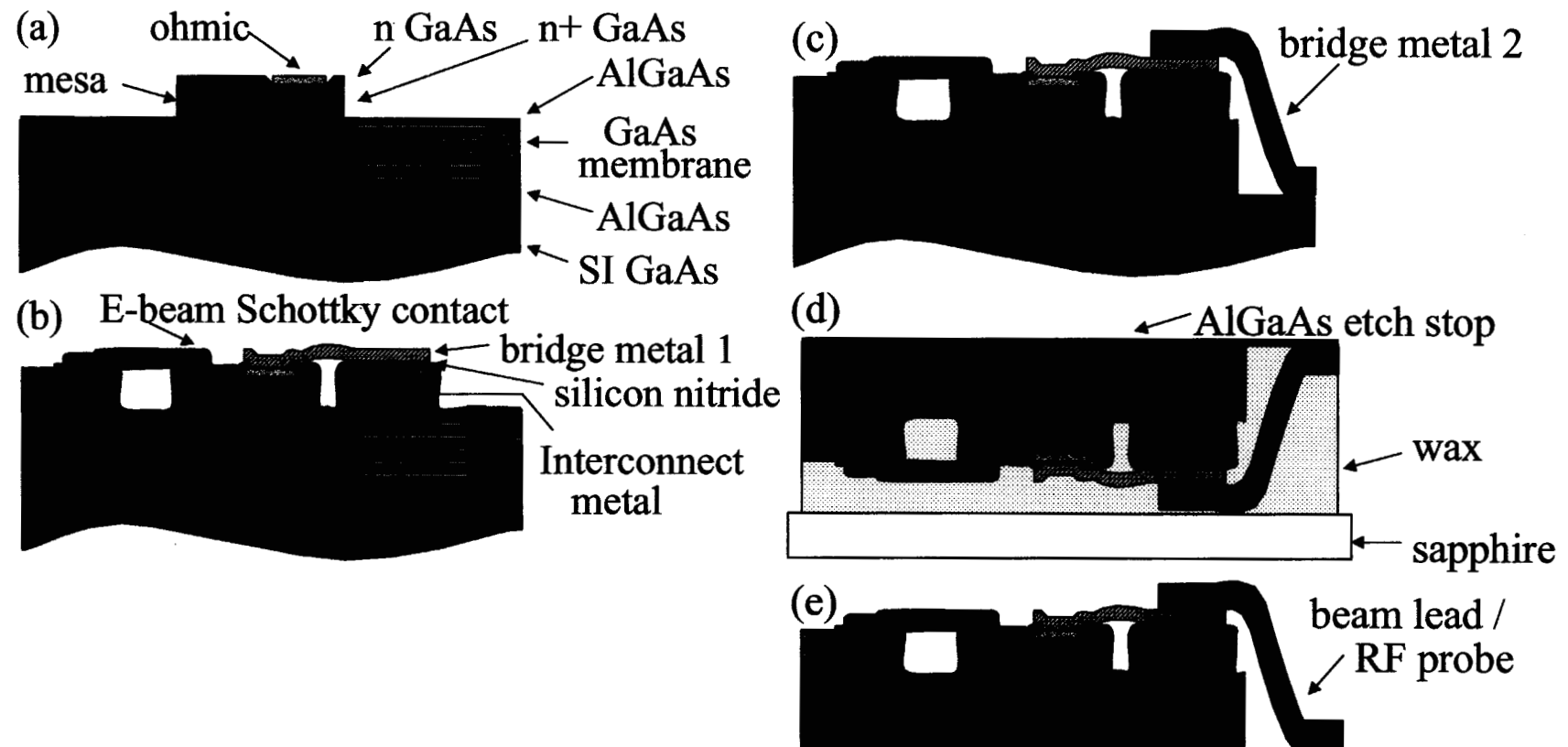


Fig. 2 High Frequency process. (a) Ohmic and mesa definition. (b) Interconnect metal and e-beam-defined Schottky deposition, followed by passivation and bridge metal 1 definition. (c) Membrane layer etch and bridge metal 2 deposition. (d) Removal of substrate with selective etch. (e) Release of device from carrier wafer.

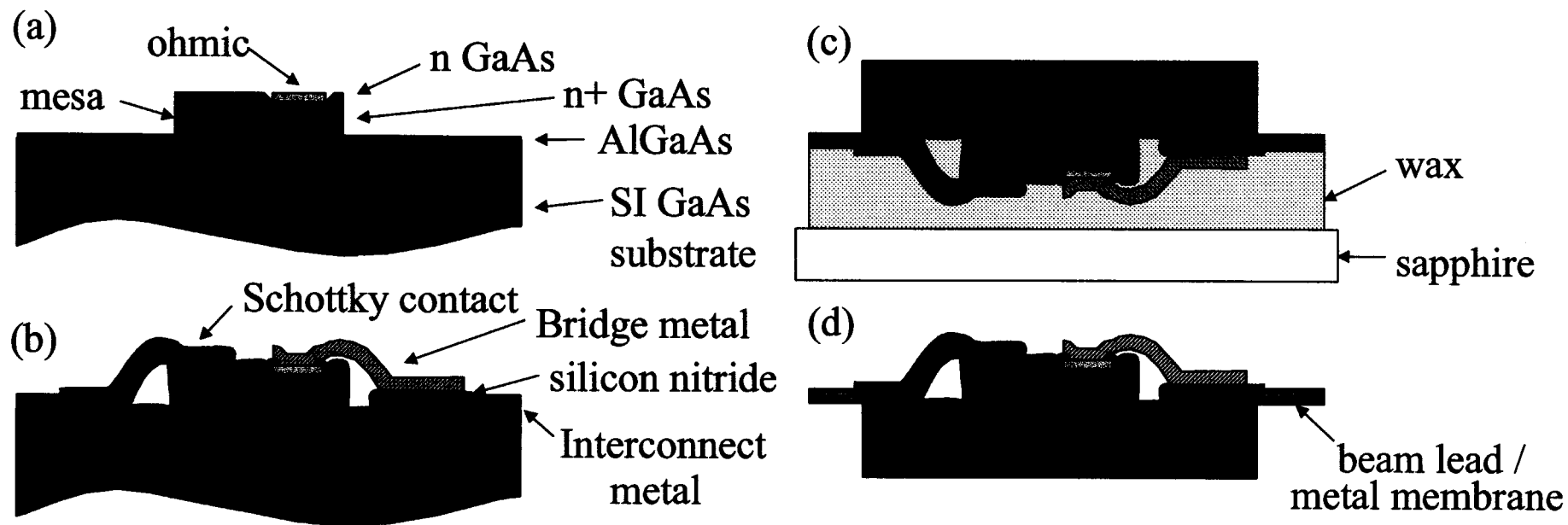
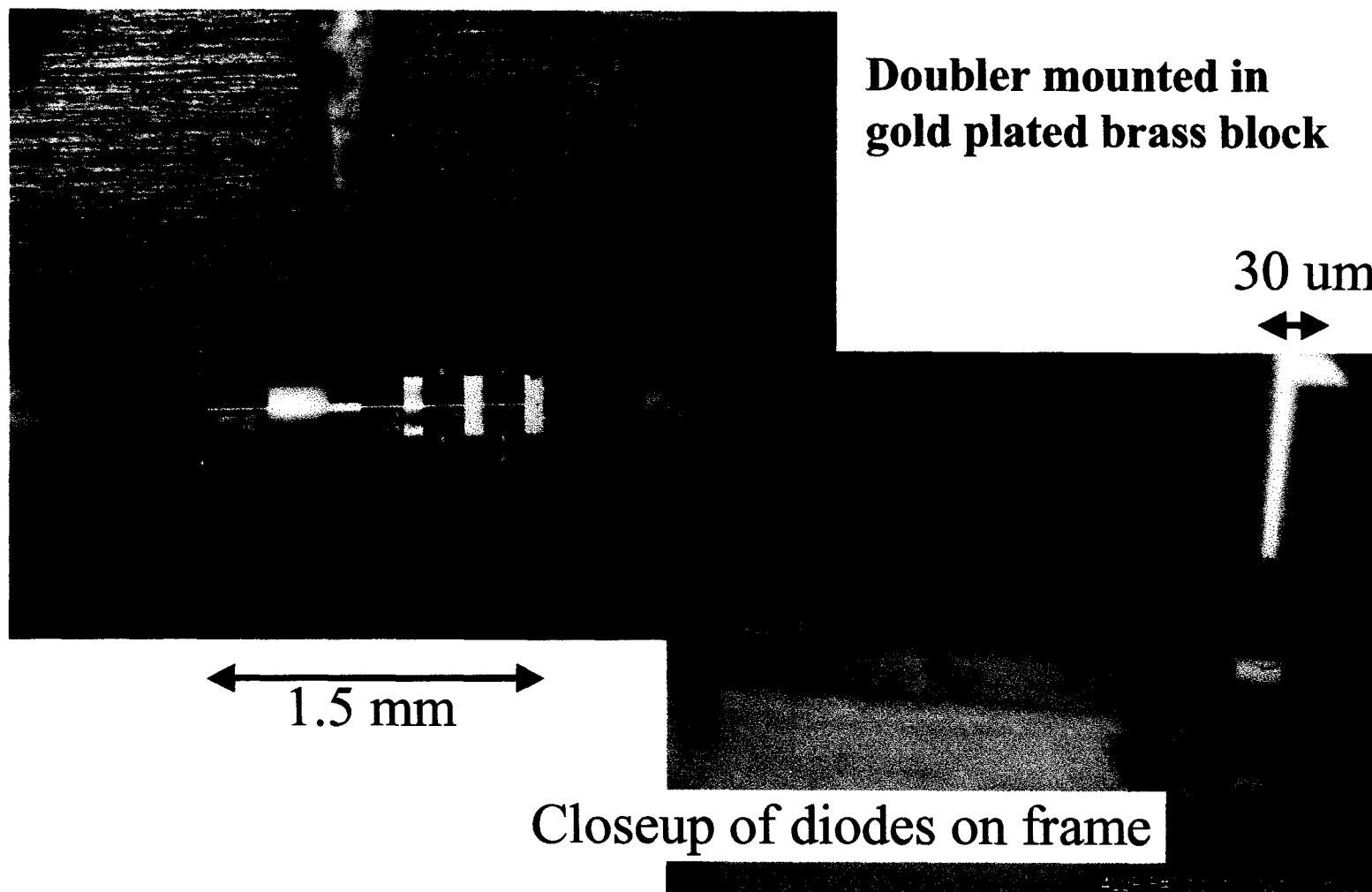


Fig. 1 Low Frequency process. (a) Ohmic and mesa definition. (b) Interconnect metal and air-bridged Schottky deposition, followed by passivation and bridge metal definition. (c) Backside thinning and device separation. (d) Release of device from carrier wafer.



Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

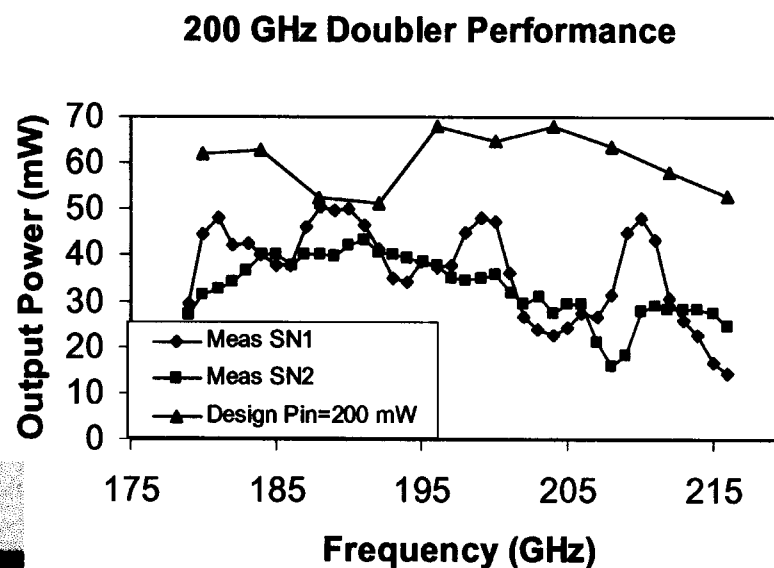
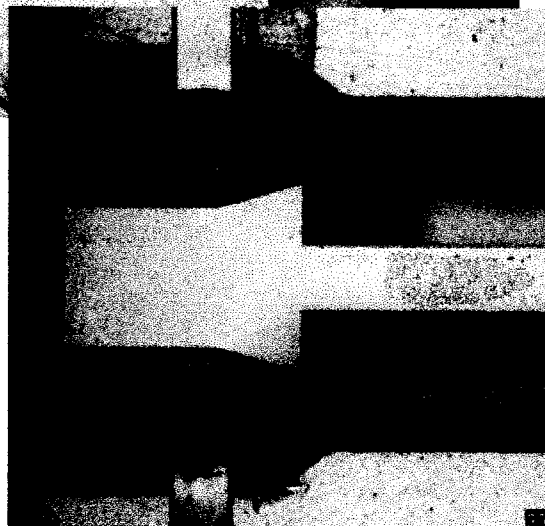
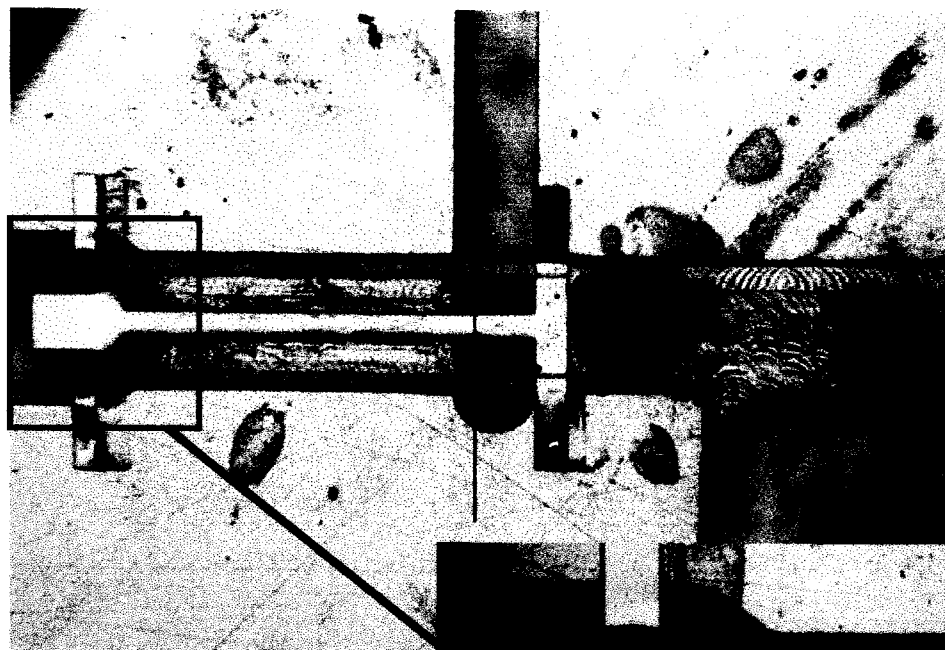
Substrateless 400 GHz Doubler in Block





Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Measured Performance of 200 GHz Doubler

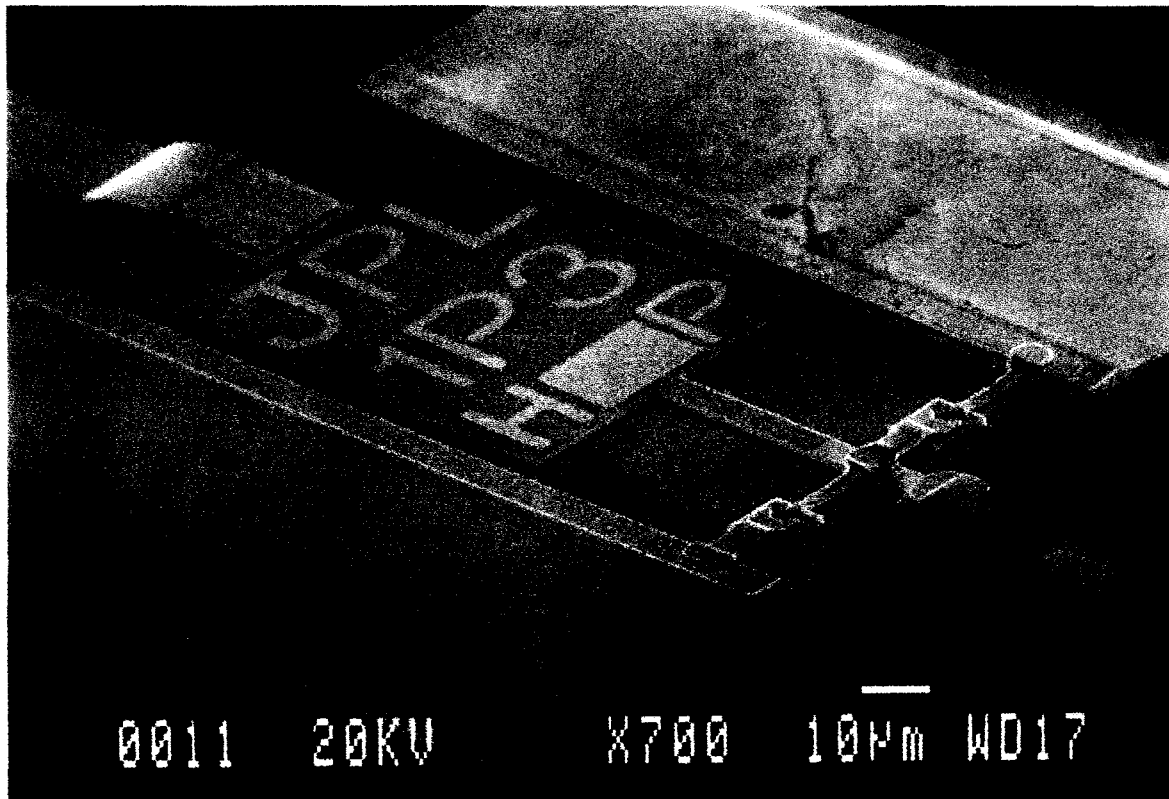




Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

1200 GHz tripler device before mounting in a split-wave guide block

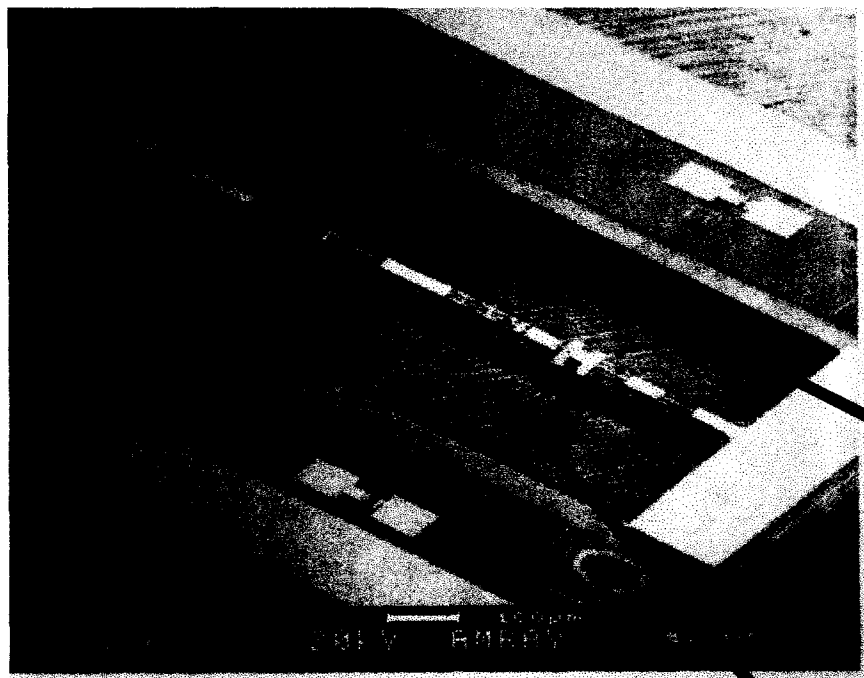
- a 3 μm thick GaAs membrane is suspended across a channel in the block
- Elimination of any thick GaAs support structure
- Two large beam leads provide the mechanical support and ground contacts to the block
- Two narrow beamleads act as RF probes in the input and output waveguides
- A similar configuration has been used in the design of a 2400 GHz doubler chip





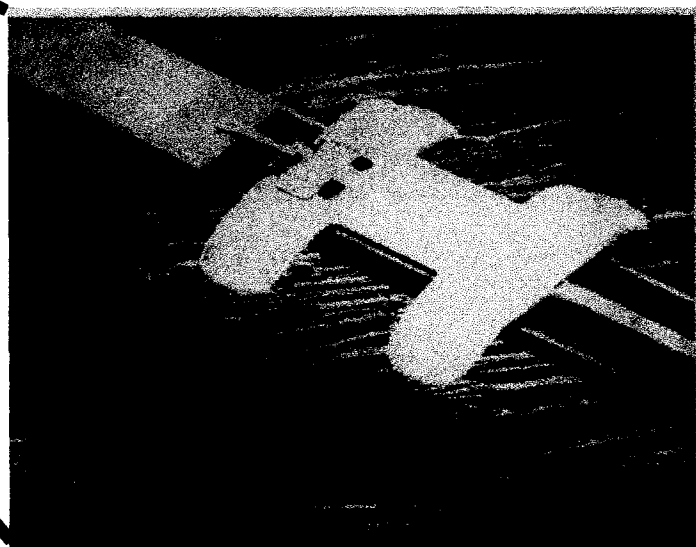
Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

MoMeD circuit with a planar GaAs Schottky-diode



Variations on first mask set:

- single and balanced antiparallel diodes
- position of diode in output waveguide
- length of anode finger
- anode area
- position of RF-short 0 μ m and 95 μ m
- square and tapered pads for diode



GaAs Membrane Parameters:

**Length=600 μ m, width=30 μ m,
thickness=3 μ m**

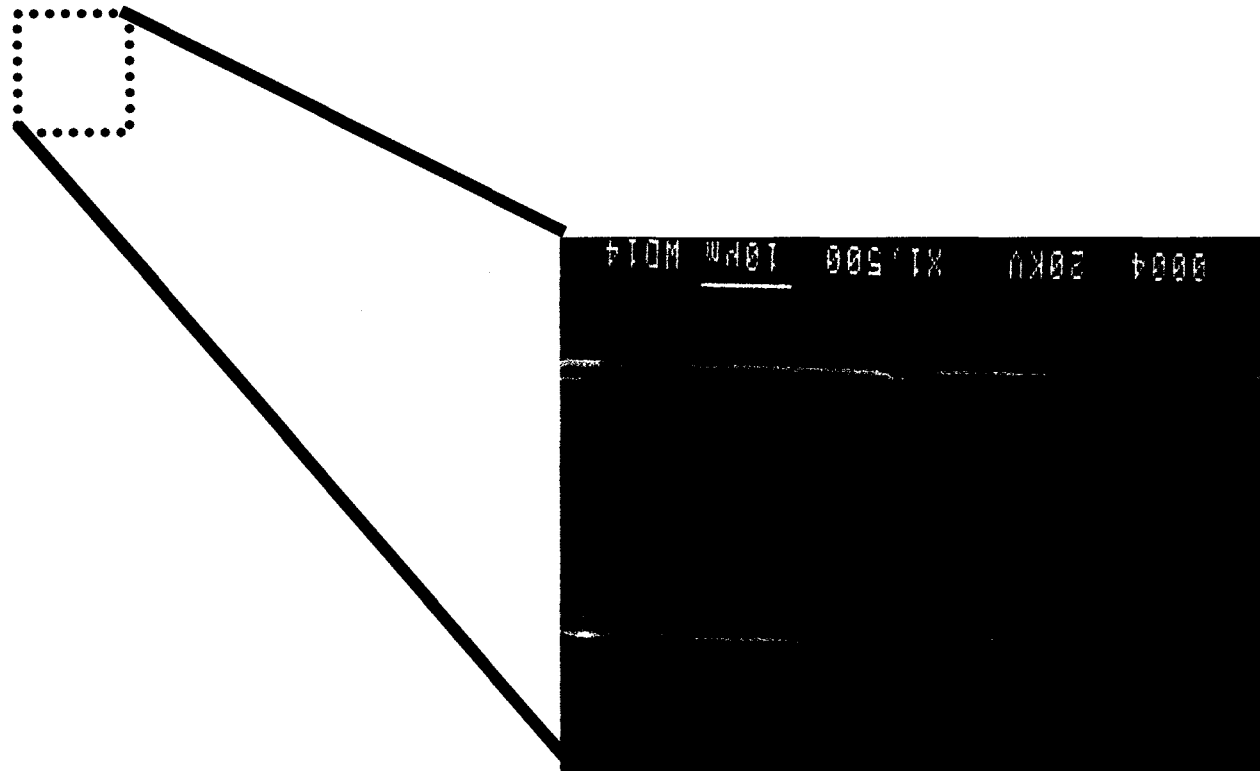
Schottky Diode parameters:

Anode dimensions: 0.4 x 1.9 μ m

$N_e = 5 \times 10^{17}/\text{cm}^3$ $R_s \sim 10$ Ohm $C_j < 2$ fF $\eta = 1.5$

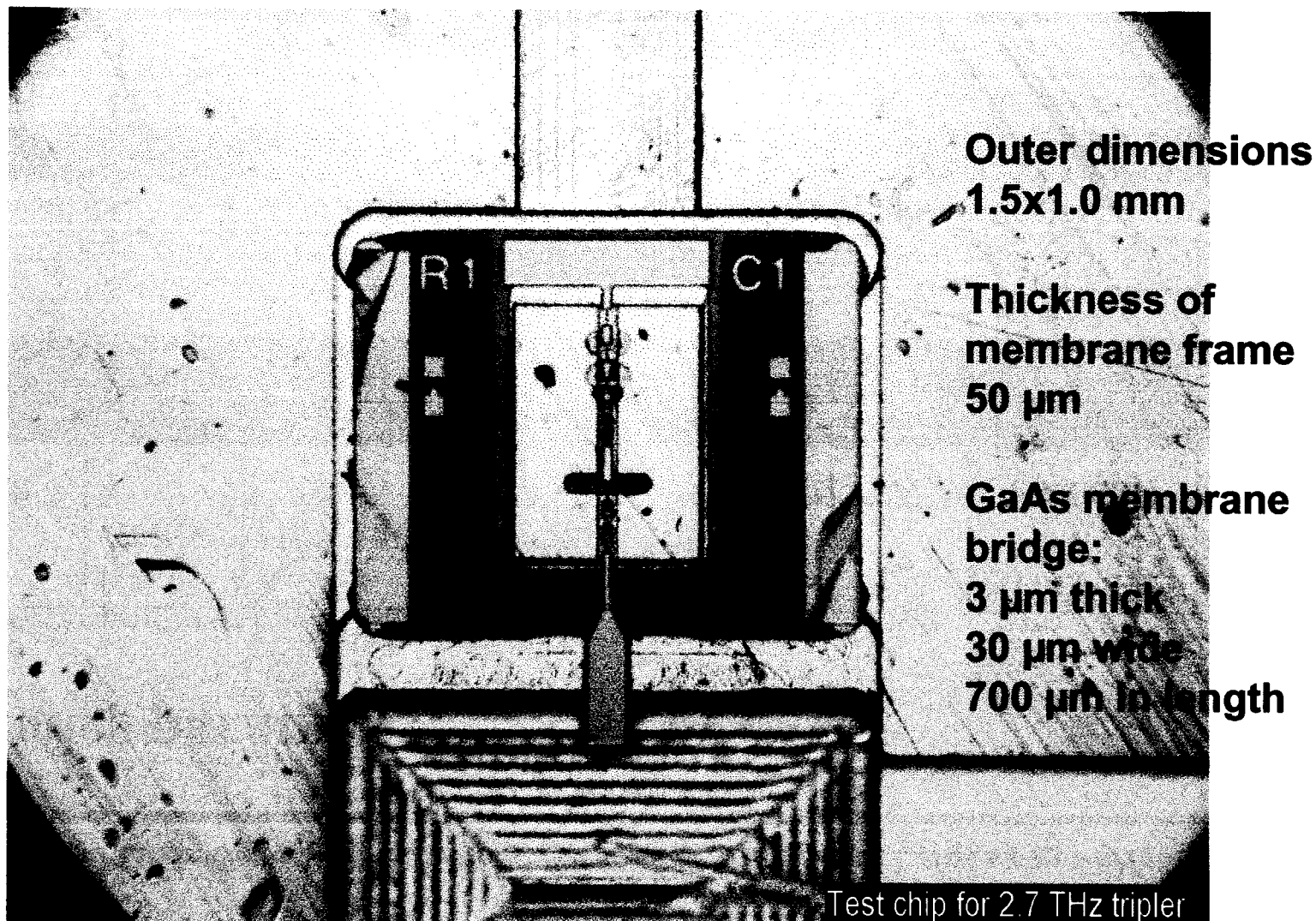


Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz





Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz





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Diodes parameter

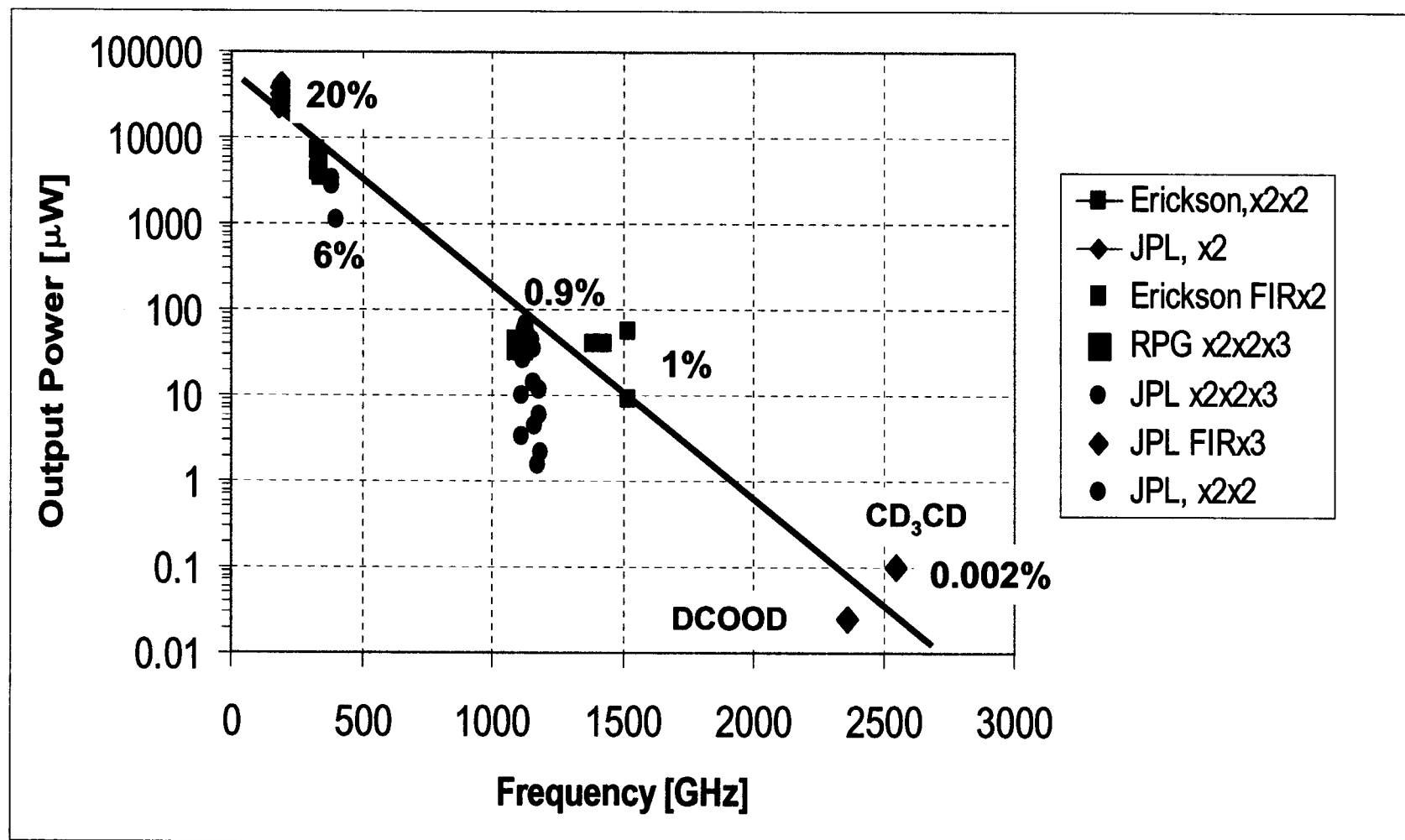
Table 2: Diode parameters for low frequency and high frequency process multiplier diodes in use at JPL.

F [GHz]	No. of diodes #	n [$10^{17}/\text{cm}^3$]	Isat [$10^{-15} \cdot \text{A}$]	Vbr [V]	Rs [Ω]	Cj0 [fF]	Anode area [$\mu\text{m} \times \mu\text{m}$]	Imax [mA]
400 ver2	2	4	0.19	5	12	10.5	3.1x1.5	4.7
800 ver1	1	2	0.038	8	43	2.64	1.5x1.0	1.5
800 ver2	1	4	0.038	5	43	2.64	1.1x1.0	1.1
1500	1	5	2.8	4.7	240	0.5	0.7x0.2	0.14
1600	1	5	2.8	4.7	240	0.5	0.7x0.2	0.14
1900	1	5	1.6	4.7	400	0.3	0.4x0.2	0.08

n=doping, Isat=saturation current, Vbr=breakdown voltage, Rs=series resistor, Imax=maximal current thru the diode area



Recent Results for solid state multiplier chains





Planar GaAs Schottky Diode Frequency Multiplier Chains up to 3THz

Publications:

Erich Schlecht, Goutam Chattopadhyay, Alain Maestrini, David Pukala, John Gill, Suzanne Martin*, Frank Maiwald and Imran Mehdi, "A High-Power Wideband Cryogenic 200 GHz Schottky "Substrateless" Multiplier: Modeling, Design and Results", Ninth International Conference on Terahertz Electronics October 14-15, 2001

CL01-2211

E. Schlecht, G. Ghattopadhyay, A. Maestrini, A. Fung, S. Martin, D. Pukala, J. Bruston and I. Mehdi, "200, 400 and 800 GHz Schottky Diode "Substrateless" Multipliers: Design and Results", International Microwave Symposium, May 2001.

CL06-2548

E. Schlecht, F. Maiwald, G. Chattopadhyay, S. Martin, and I. Mehdi, "DESIGN CONSIDERATIONS FOR HEAVILY-DOPED CRYOGENIC SCHOTTKY DIODE VARACTOR MULTIPLIERS", 12th International Symposium on Space Terahertz Technology February 14-16, 2001

CL01-0380

Frank Maiwald, Suzanne Martin, Jean Bruston, Alain Maestrini, Timothy Crawford, Peter H. Siegel, "Design and Performance of a 2.7 THz Waveguide Tripler ", 12th International Symposium on Space Terahertz Technology February 14-16, 2001

ABS -

CL00-2481

PAPER

CL01-2272

J. Bruston, E. Schlecht, A. Maestrini, F. Maiwald, S.C. Martin, R.P. Smith[†], I. Mehdi, P.H. Siegel, and J. Pearson, "Development of 200 Ghz to 2.7 Thz Multiplier Chains for Submillimeter-wave Heterodyne Receivers", SPIE International Symposium on Astronomical Telescopes and Instrumentation, 29 March 2000

CL00-0373

Suzanne Martin, Barbara Nakamura, Andy Fung, Peter Smith[†], Jean Bruston, Alain Maestrini, Frank Maiwald, Peter Siegel, Erich Schlecht, and Imran Mehdi, "Fabrication of 200 to 2700 GHz Multiplier Devices using GaAs and Metal Membranes", IEEE MTT-S International Microwave Symposium, Phoenix, Arizona, May 20-25, 2001

CL00-2546